Coherent supercontinuum generation in photonic crystal fiber with all-normal group velocity dispersion

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Abstract: We demonstrate supercontinuum generation in a photonic crystal fiber with all-normal group velocity dispersion. Pumping a short section of this fiber with compressed pulses from a compact amplified fiber laser generates a 200 nm bandwidth continuum with typical self-phase-modulation characteristics. We demonstrate that the supercontinuum is compressible to a duration of 26 fs. It therefore has a high degree of coherence between all the frequency components, and is a single pulse in the time domain. A smooth, flat spectrum spanning 800 nm is achieved using a longer piece of fiber.

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OCIS codes: (320.6629) Supercontinuum generation; (060.4005) Microstructured fibers.

References and links

1. J. C. Knight, "Photonic crystal fibres," Nature **424**(6950), 847–851 (2003).
2. J. K. Ranka, R. S. Windeler, and A. J. Stentz, "Visible continuum generation in air-silica microstructure optical fibers with anomalous dispersion at 800 nm," Opt. Lett. **25**(1), 25–27 (2000).
3. K. L. Corwin, N. R. Newbury, J. M. Dudley, S. Coen, S. A. Diddams, B. R. Washburn, K. Weber, and R. S. Windeler, "Fundamental amplitude noise limitations to supercontinuum spectra generated in a microstructured fiber," Appl. Phys. B **77**(2-3), 269–277 (2003).
4. J. M. Dudley, and S. Coen, "Coherence properties of supercontinuum spectra generated in photonic crystal and tapered optical fibers," Opt. Lett. **27**(13), 1180–1182 (2002).
5. H. N. Paulsen, K. M. Hilligse, J. Thøgersen, S. R. Keiding, and J. J. Larsen, "Coherent anti-Stokes Raman scattering microscopy with a photonic crystal fiber based light source," Opt. Lett. **28**(13), 1123–1125 (2003).
6. H. A. Rinia, M. Bonn, M. Müller, and E. M. Vartiainen, "Quantitative CARS spectroscopy using the maximum entropy method: the main lipid phase transition," ChemPhysChem **8**(2), 279–287 (2007).
7. J. M. Dudley, and S. Coen, "Fundamental limits to few-cycle pulse generation from compression of supercontinuum spectra generated in photonic crystal fiber," Opt. Express **12**(11), 2423–2428 (2004).
8. Th. Udem, R. Holzwarth, and T. W. Hänsch, "Optical frequency metrology," Nature **416**(6877), 233–237 (2002).
9. B. Povazay, K. Bizheva, A. Unterhuber, B. Hermann, H. Sattmann, A. F. Fercher, W. Drexler, A. Apolonski, W. J. Wadsworth, J. C. Knight, P. S. Russell, M. Vetterlein, and E. Scherzer, "Submicrometer axial resolution optical coherence tomography," Opt. Lett. **27**(20), 1800–1802 (2002).
10. J. M. Dudley, and S. Coen, "Supercontinuum generation in photonic crystal fiber," Rev. Mod. Phys. **78**(4), 1135–1184 (2006).
11. W. H. Reeves, D. V. Skryabin, F. Biancalana, J. C. Knight, P. S. Russell, F. G. Omenetto, A. Efimov, and A. J. Taylor, "Transformation and control of ultra-short pulses in dispersion-engineered photonic crystal fibres," Nature **424**(6948), 511–515 (2003).
12. M. N. Islam, G. Sucha, I. Bar-Joseph, M. Wegener, J. P. Gordon, and D. S. Chemla, "Femtosecond distributed soliton spectrum in fibers," J. Opt. Soc. Am. B **6**(6), 1149–1158 (1989).
13. J. Herrmann, U. Griebner, N. Zhavoronkov, A. Husakou, D. Nickel, J. C. Knight, W. J. Wadsworth, P. St. J. Russell, and G. Korn, "Experimental evidence for supercontinuum generation by fission of higher-order solitons in photonic fibers," Phys. Rev. Lett. **88**(17), 173901 (2002).
14. G. P. Agrawal, *Nonlinear Fiber Optics*, 4th Edition (Academic Press, 2007)
15. A. M. Heidt, "Pulse preserving flat-top supercontinuum generation in all-normal dispersion photonic crystal fibers," J. Opt. Soc. Am. B **27**(3), 550–559 (2010).
16. G. Humbert, W. Wadsworth, S. Leon-Saval, J. Knight, T. Birks, P. St. J. Russell, M. Lederer, D. Kopf, K. Wiesauer, E. Breuer, and D. Stifter, "Supercontinuum generation system for optical coherence tomography based on tapered photonic crystal fibre," Opt. Express **14**(4), 1596–1603 (2006).

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17. L. E. Hooper, P. J. Mosley, A. C. Muir, W. J. Wadsworth, and J. C. Knight, "All-normal dispersion photonic crystal fiber for coherent supercontinuum generation," in *Conference on Lasers and Electro-Optics*, OSA Technical Digest (CD) (Optical Society of America, 2010), paper CTuX4.
18. K. Saitoh, and M. Koshiba, "Empirical relations for simple design of photonic crystal fibers," Opt. Express **13**(1), 267–274 (2005).
19. *http://sydney.edu.au/science/physics/cudos/research/mofsoftware.shtml* [Accessed 12/11/10]
20. T. P. White, B. T. Kuhlmey, R. C. McPhedran, D. Maystre, G. Renversez, C. M. de Sterke, and L. C. Botten, "Multipole method for microstructured optical fibers. I. Formulation," J. Opt. Soc. Am. B **19**(10), 2322–2330 (2002).
21. F. Gérôme, K. Cook, A. K. George, W. J. Wadsworth, and J. C. Knight, "Delivery of sub-100fs pulses through 8m of hollow-core fiber using soliton compression," Opt. Express **15**(12), 7126–7131 (2007).
22. J. M. Stone, and J. C. Knight, "Visibly "white" light generation in uniform photonic crystal fiber using a microchip laser," Opt. Express **16**(4), 2670–2675 (2008).
23. C. Finot, B. Kibler, L. Provost, and S. Wabnitz, "Beneficial impact of wave-breaking for coherent continuum formation in normally dispersive nonlinear fibers," J. Opt. Soc. Am. B **25**(11), 1938–1948 (2008).
24. R. L. Fork, O. E. Martinez, and J. P. Gordon, "Negative dispersion using pairs of prisms," Opt. Lett. **9**(5), 150–152 (1984).
25. D. T. Reid, M. Padgett, C. McGowan, W. E. Sleat, and W. Sibbett, "Light-emitting diodes as measurement devices for femtosecond laser pulses," Opt. Lett. **22**(4), 233–235 (1997).

1. Introduction

High-brightness broadband light sources are essential for many applications, and supercontinuum sources based on photonic crystal fiber (PCF) are now widely used [1,2]. However, due to the nature of the spectral broadening processes involved, typical PCF supercontinuum sources suffer from fluctuations not only in the intensity [3] but also in the arrival time (and hence relative phase) of different spectral components [4]. This noise limits resolution or precision in many applications including nonlinear microscopy [5,6], ultra-short pulse generation [7], frequency metrology [8], and optical coherence tomography [9]. All of these areas would benefit from a broadband source which is stable and coherent over its entire spectral bandwidth.

Supercontinuum generation in photonic crystal fibers is a well studied process, and can comprise many different nonlinear effects such as self- and cross-phase modulation, soliton effects, Raman scattering, modulation instability and four wave mixing. For a comprehensive description of supercontinuum generation in PCF the reader is directed to [10]. Which broadening effects dominate depends upon both the pump laser parameters and the nonlinearity and dispersion of the fiber [4,10,11]. Most "white light" supercontinuum spectra are generated by pumping highly nonlinear PCF with femtosecond or picosecond pulses in the anomalous group velocity dispersion (GVD) regime of the PCF, close to the zero-dispersion wavelength (ZDW). In this case, spectral broadening is dominated by soliton effects where higher order solitons break down into a series of fundamental solitons. Each fundamental soliton is then Raman shifted to a longer wavelength [12,13], and as a result of dispersion the pulse breaks up into a series of sub-pulses in the temporal domain. This process produces a spectrum with a fine and complex structure, which is very sensitive to pump pulse fluctuations, resulting in large differences in spectral structure from pulse to pulse [4,10]. Averaging over many pulses may produce a smooth and flat spectrum, but due to the fluctuations in relative phase and intensity there will be low coherence across the bandwidth [4,10].

In order to reduce this noise, soliton effects must be eliminated. This can be done either by careful choice of input pulse parameters [3,4,10] or by generating the supercontinuum solely in the normal GVD regime in which solitons cannot form and spectral broadening is mainly through self phase modulation [14]. Self phase modulation (SPM) is an intrinsically deterministic process that preserves the coherence of the input pulses. Therefore generating supercontinuum in the normal GVD regime is expected to produce high spectral coherence and stability [15]. The achievable bandwidth, however, cannot be expected to compete with that from anomalous-dispersion fibers, due to the dispersive spreading of the broadened spectrum, rather than compression as in the case of anomalous-dispersion fiber. Therefore careful dispersion engineering is required to maximize the spectral bandwidth. On the other

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hand, confining the light to a specific spectral region is beneficial in applications where high spectral power density is required [5].

One possibility for generating supercontinuum in the normal GVD regime is to pump conventional fiber far below the ZDW, so that the generated spectrum does not extend into the anomalous dispersion regime. However, this would require high power or very short pulses to overcome the short effective interaction length due to the high value of dispersion far from the ZDW. A more efficient method, and the one used in this work, is to generate supercontinuum in photonic crystal fiber which has an all-normal GVD profile, with a low value of dispersion at the pump wavelength. Over a small range of pitch (hole-to-hole distance) and hole diameter it is possible to fabricate PCF with all-normal dispersion profiles. PCF with all normal dispersion designed for pumping at 800 nm have previously been fabricated using a post-processing method [16], however using this technique the available fiber length, and hence spectral broadening, is limited. In this paper we present PCF which is designed to have all-normal GVD for pumping at 1064 nm, with no post-processing required [17]. Similar all-normal dispersion fibers for pumping at 1064 nm have been the subject of a recent extensive numerical study [15]. These are predicted to exhibit highly coherent supercontinua which are flat and which contain only a single pulse in the time domain. We present experimental results of supercontinuum generation in PCF with an all-normal GVD profile, and demonstrate re-compression of the spectrum generated in a short fiber length.

2. All-normal dispersion fiber

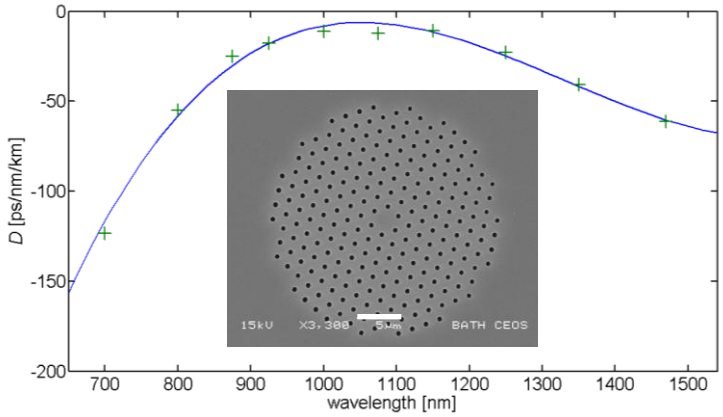

Fig. 1. Scanning electron microscope image of fiber cross-section with scale bar 5 µm (inset), and measured dispersion, *D*, of the all-normal dispersion PCF. Crosses show the two-point differences derived from the measured values of group delay, and the curve is the derivative of a 4th order polynomial fit to the group delay data.

A PCF was designed with all-normal GVD, which is low and flat at 1064 nm to allow for maximum spectral broadening and to reduce the effects of third-order dispersion. The optimal values of pitch and hole diameter were obtained through modeling the GVD using an empirical formula [18] and multipole mode solver software "CUDOS MOF Utilities" [19,20]. These were found to be pitch = 1.60 µm and hole diameter/pitch ratio = 0.38. The structure consists of a solid silica core, surrounded by 8 rings of air holes to ensure sufficiently low confinement loss. The fiber was fabricated from fused silica glass using the stack and draw method, and the final PCF has measured pitch = 1.65 µm and a hole diameter/pitch ratio = 0.32. The measured GVD profile of the fiber is shown in Fig. 1, with a scanning electron microscope image of the fiber cross-section inset. Dispersion measurements were carried out using white light interferometry with a supercontinuum source pumped at 1064 nm, and hence there is reduced accuracy in the data near this wavelength. The GVD profile is as required; all-normal, and low and flat around 1064 nm. The value of GVD at 1064 nm is –6 ps/nm/km, according to the fit.

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3. Supercontinuum generation

The all-normal dispersion fiber described above was used to generate supercontinuum. The pump source used consisted of an amplified mode locked fiber laser (*Fianium Ltd*) which produced strongly chirped pulses, and a 15 m length of hollow core fiber for pulse re-compression [21]. The fiber laser output pulses were centered at 1064 nm with average power of 10 W at a repetition rate of 20 MHz. These pulses were coupled into the hollow core fiber in which they were first linearly compressed, and then formed solitons [21] which Raman shifted to 1075 nm. After the hollow core fiber the output was filtered to remove the dispersive wave associated with the soliton, leaving almost transform-limited pulses with average power of 2 W. The pulse lengths varied in the range 350-450 fs depending on the input coupling conditions to the hollow core fiber. These pulses were then attenuated using polarisation optics and coupled into the fiber being tested. The output spectra were measured using an optical spectrum analyzer. For the all-normal dispersion fiber the coupling efficiency was ~50% and the input power was limited to 800 mW due to fiber end damage. The set up is represented in Fig. 2.

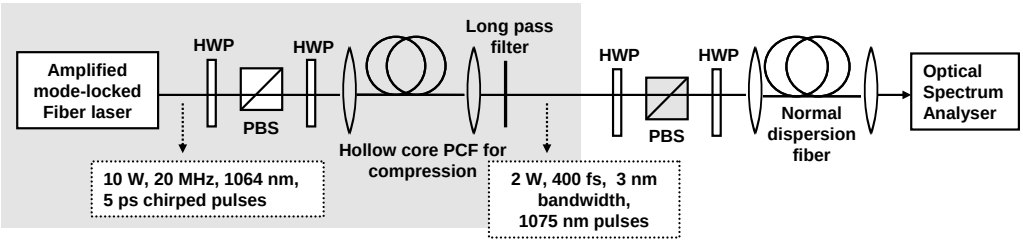

Fig. 2. Set up for generating supercontinuum in the all-normal-dispersion fiber. Gray box indicates the pump source. HWP, half wave plate; PBS, polarizing beam splitter.

Supercontinuum was generated in different lengths of the all-normal dispersion fiber as well as a state-of–the-art anomalous dispersion supercontinuum PCF [22] and a standard single-mode step-index fibre (*Nufern,* 980HP) using the same input pulses for comparison. Figure 3(a) shows the spectrum generated in a 4 cm length of all normal dispersion fiber. The spectrum has a shape characteristic of self phase modulation and a spectral width of approximately 200 nm (FWHM). A self phase modulation spectrum was obtained by numerical modeling, shown in Fig. 3(b). The model includes only self phase modulation, neglecting all other nonlinear effects and dispersion. A pulse length of 350 fs, average power 450 mW and nonlinear parameter 0.0194 $(\mathrm{Wm})^{-1}$ was used. The modeled and measured spectra are similar, suggesting that self phase modulation dominates broadening in the all-normal dispersion fiber supercontinuum. Figure 3(c) shows the spectrum obtained with the same input pulses in 4 cm of the standard single mode fiber. This fiber has high normal dispersion (approximately – 45 ps/nm/km) at the pump wavelength (1075nm). The spectrum still has a shape characteristic of self phase modulation, however, due to the high dispersion at the pump wavelength, the spectral broadening is limited while the dispersion slope leads to decreased spectral symmetry. Figure 3(d) shows the spectrum generated in a 4 cm length of highly nonlinear anomalous-dispersion supercontinuum fiber. The spectrum has a large bandwidth and fine and complex structure, suggesting that the dominant broadening mechanisms in this case are due to soliton effects.

Figure 3(e) shows the spectrum generated in 1 m of the all-normal dispersion fiber compared to the spectrum generated in 4 cm from Fig. 3(a), on a logarithmic scale. The 1 m spectrum does not have the clear self phase modulation peaks seen in the 4 cm spectrum, and has a bandwidth increased to 800 nm (FWHM). The flattening of the spectrum in the longer fiber length is a result of optical wave breaking, as described in reference [23].

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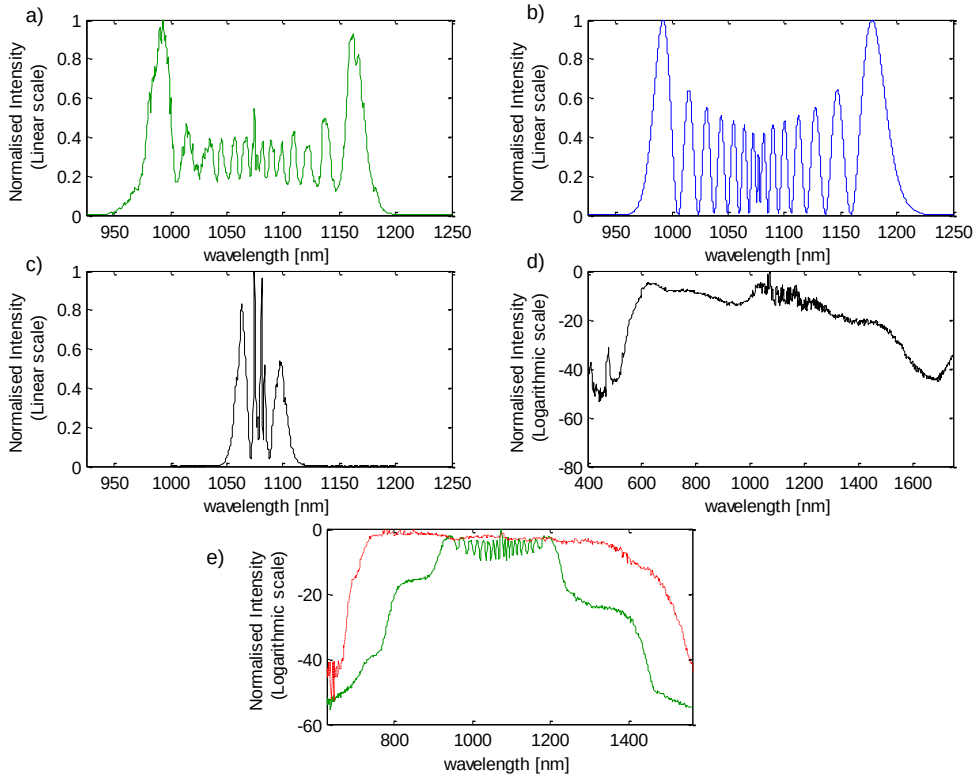

Fig. 3. Spectra generated all with same input pulse conditions: (a) 4 cm all-normal dispersion fiber, (b) Pure self phase modulation spectrum predicted by modeling, neglecting other nonlinear effects and dispersion, (c) 4 cm conventional single mode fiber (*Nufern*, 980HP), (d) spectrum generated in 4 cm "white light" PCF [22] and (e) 4 cm (solid green) and 1 m (dashed red) all-normal dispersion fiber, shown on a logarithmic scale.

4. Pulse re-compression

The degree of spectral coherence determines the compressibility of supercontinuum pulses [7]. In order to demonstrate the coherence of the all-normal-dispersion supercontinuum, re-compression experiments were carried out. The spectrum generated in a 4 cm length of the fiber is expected to have a predominantly linear chirp, and to consist of a single pulse in the time domain [15]. Therefore in order to compensate for the dispersion we used a simple double-pass prism pair compressor [24]. The dispersion of the prism compressor was adjusted by varying the distance between two SF11 prisms. The pulse lengths were measured using an interferometric autocorrelator based on two-photon absorption in a light-emitting diode [25]. It was checked experimentally that the light emitting diode exhibited two-photon absorption across the full bandwidth of the pulses being measured, with low spectral dependence.

Autocorrelation traces were obtained at different stages of the experiment, and are shown in Fig. 4. Figure 4(a) is the autocorrelation trace of the input pulses (output from hollow core fiber) and this gives an optical pulse FWHM of 420 fs assuming a sech^2 temporal profile. The autocorrelation of the un-compressed output from the all-normal dispersion fiber is shown in Fig. 4(b) and has the characteristic shape of a highly chirped pulse. The pulse length can be estimated from looking at the width of the pedestal which is around 1 ps. Figure 4(c) shows the re-compressed pulse emerging from the prism pair. It can be seen that the linear chirp has been removed since the baseline is flat. The pulse has a FWHM of approximately 26 fs assuming sech^2 temporal profile. The shoulders on the trace are due to the small amount of higher order dispersion in the fiber which cannot be compensated for with the prisms. The

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irregularity of the wings of the autocorrelation traces in Fig. 4(b) and 4(c) is due to fluctuations in both the laser pulse amplitude and coupling into the hollow core and supercontinuum PCF. The fluctuations are fast compared to the time over which the autocorrelation trace is recorded. The transform limit for this spectrum is approximately 14 fs, which is comparable to our measured result of 26 fs. This result shows that the supercontinuum from the all-normal dispersion fiber has a high degree of coherence and consists of a single pulse in the time domain.

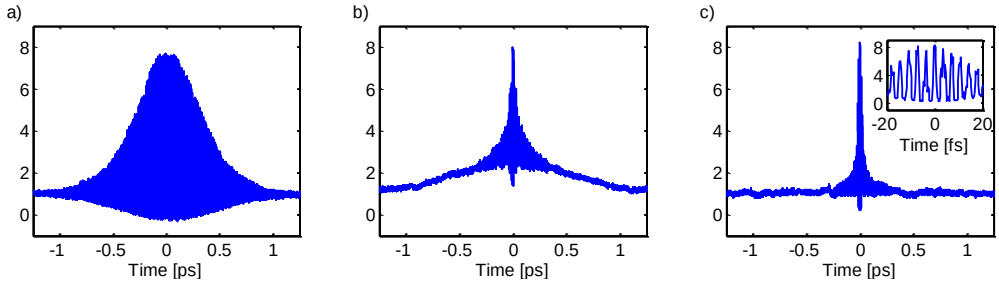

Fig. 4. Normalised autocorrelation traces of: (a) the output from the hollow core, showing pulse length of 420 fs assuming $sech^2$ shape, (b) pulse after 4 cm all-normal dispersion fiber and (c) re-compressed supercontinuum pulse. Inset shows central part of autocorrelation trace expanded so that interference is visible.

5. Conclusion

Many applications of supercontinuum generation would benefit from increased stability and coherence. A fiber with all-normal group velocity dispersion has been fabricated and demonstrated as a method to produce low noise supercontinuum. Using the arrangement described, a supercontinuum generated by pure self phase modulation, spanning 200 nm and with a mean spectral power density of approximately 2 mW/nm, was achieved in a 4 cm length of all-normal dispersion PCF. Furthermore, a broad and flat spectrum was generated in 1 m of all-normal dispersion PCF. Re-compression of the short fiber pulses has been carried out and pulse lengths obtained are within a factor of two of the transform limit, demonstrating a high degree of spectral coherence and a single pulse in the time domain. A similar all-normal dispersion fiber can be designed for pumping at 800 nm, for use with Ti:Sapphire systems.

Acknowledgements

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